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Improving the accuracy of a machine tool with three linear axes using a laser tracker as measurement system

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Abstract

This paper presents a real way to improve machine tool accuracy using interferometry techniques based on laser tracker as measurement system. This is based on an indirect measurement of the geometric error of the MT; characterizing their combined effect though volumetric verification.

This technique can be used to verify all types of machine through its kinematic model, relating measured points with the laser tracker and nominal points. Using non-lineal optimization techniques the difference between pair of points are reduced. Finally, it provides the approximation functions of the machine tool geometric errors used to compensate theirs influence on MT accuracy.

As it is a mathematical compensation result of an optimization procedure, the improvement on MT accuracy should be validate using the same or external measurement system. This paper shows that volumetric verification provides an real improvement of the MT accuracy.

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Keywords: volumetric verification; geometrical errors; kinematic model; laser tracker; laser interferometer

Nomenclature

LT	laser tracker
MT	machine tool
NC	numerical control
CS	coordinate system

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1. Introduction

Currently, one of the most important competition aspects on MT sector is the accuracy of manufactured parts. Demand for reliability and productive capacity cause that many current production systems are obsolete and can not reach specification requires. Defective parts increase costs and production time; reducing MT productive capacity as a result of an inefficient process of work.

Errors of a machine tool are originated from various sources of error, static from its kinematic errors and therefore its positioning accuracy, dynamics in its usage and thermal factors such as environmental conditions or temperature. In the same way, errors are divided in systematic and random errors as well as quasi-static errors and dynamic errors. Geometric and thermal errors are the dominant ones, providing between 40% and 70% of the total error [1].Traditionally, verification trays to improve MT accuracy using compensation techniques to minimize the influence of its geometric errors.

Geometric errors can be measured individually or all together. If errors are measured individually, it is named direct measurement. These methods determines the influence of each error from each axis in a particular position of the workspace of the machine tool; providing its physical behaviour [2, 3]. However, the relationship between geometric errors is not studied and approximation functions obtained are directly extrapolated to the rest of the MT workspace. Similarly, each error needs an own assembly measurement procedure and data treatment increasing substantially verification time [1]. The requirements of verification in a short time with high accuracy demand verification using indirect measurement of errors; especially in machine tools with long range of movement. Indirect measurement produces a global correction of the MT workspace based on multi-axis movement and its kinematic model. Indirect measurement based on measurement systems such as ball bar or laser interferometry are used in volumetric verification techniques [1, 4-6]. Within different methods of volumetric verification, laser interferometry has distinguished itself due to its reduce verification time and capability to measure long range. MT. Volumetric verification is based on minimizing the difference between nominal and real points, in order to characterize the influence of each geometric error through the MT kinematic model and non-lineal optimization techniques. Therefore, approximation functions obtained result of optimization process are affected by identification strategies, measurement systems, etc [4-6].

This paper presents steps required to perform the volumetric verification and compensation of a real machine with three linear axes, using a laser tracker as the measurement system based on the kinematic model of the MT. As approximation functions provide a mathematical compensation of combined geometric errors of verification points, theirs behaviour and adequacy to improve the global accuracy of the MT in all its workspace is study using control points.

2. Methodology and Experimental Procedure

2.1 Kinematic model and equation of motion

Machine tool geometric errors analysis depends on the type and configuration of the MT. Structural elements such as joints, couplings or gears define the kinematic chain of the MT. To create the kinematic model of a machine tool its sequence of movements and the errors that affect the MT, as well as its structure and type of machine must be analyzed.

The MT to verify is a milling machine with three lineal axes. Therefore, to define its kinematic chain four different coordinate systems are needed (Figure 1):

- CS-O: Origen of the machine tool
- CS-X: Associated with the movement of X axis.
- CS-Y: Associated with the movement of Y axis.
- CS-Z: Associated with the movement of Z axis.
- CS-T: Associated with the origin of the tool.

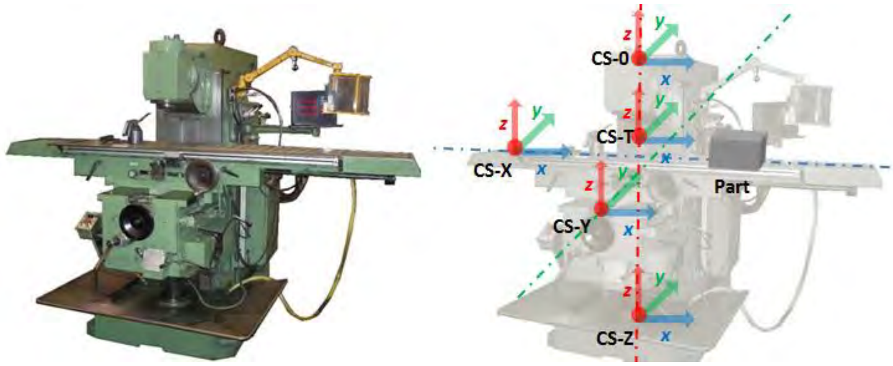

Fig. 1. Machine tool with configuration XFYZ

The position of the tool relative to the part can be determined mathematically as a function of the movement of the machine through its kinematic scheme (Figure 2 left). As X axis is associated with movement of the part and Y Z axes are associated with the movement of to the tool, its machine tool configuration is XFYZ where F represents the bed of the machine.

Volumetric verification requires that measurement system shows the same errors as a part to be machined. So the measurement system (laser tracker) must be placed on machine bed and retro-reflector in the tool. As laser tracker in an absolute measurement system, the relationship between CS- LT and CS-O is obtained using least squares fit and it is introduced in the kinematic model of the machine. (Fig. 2 right)

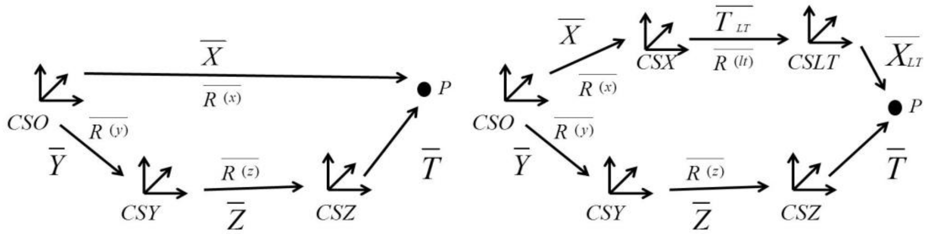

Fig. 2. Kinematic scheme with and without laser tracker (left-right)

After the kinematic scheme of the machine is generated, it is necessary to obtain the mathematical relationship that transforms the machine coordinates introduced by numerical control P (x, y, z) to laser tracker coordinates $\overline{X_{LT}}$. This is done through the equation of motion of the machine (eq. 1). This is determined by values of the movements of the machine axes defined by nominal coordinates P (x y z) and geometric errors of each axis.

$$\overline{X_{LT}} = \overline{R_{LT}^{-1}}\left(\overline{R_X^{-1}}\left(\overline{R_Y}\left(\overline{R_Z}\,\overline{T} + \overline{Z}\right) + \overline{Y} - \overline{Z}\right) - \overline{T_{LT}}\right) \quad (1)$$

Where:

$\overline{T}$ is the offset of the tool.

$$\overline{T} = \begin{pmatrix} x_t \\ y_t \\ z_t \end{pmatrix} \quad (2)$$

$\overline{R_k}$ represents the rotational error matrix in the axis k of the tool with $k = x, y, z$.

$$\overline{R_{(k)}} = \begin{pmatrix} 1 & -\varepsilon_Z(k) & \varepsilon_Y(k) \\ \varepsilon_Z(k) & 1 & -\varepsilon_X(k) \\ -\varepsilon_Y(k) & \varepsilon_X(k) & 1 \end{pmatrix} \tag{3}$$

$\overline{X}$ represents the linear error vector in the X-axis of the milling machine.

$$\overline{X} = \begin{pmatrix} -x + \delta_X(x) \\ \delta_Y(x) \\ \delta_Z(x) \end{pmatrix} \tag{4}$$

$\overline{Y}$ represents the linear error vector in the Y-axis of the milling machine.

$$\overline{Y} = \begin{pmatrix} -y \cdot \varepsilon_{XY} + \delta_X(y) \\ y + \delta_Y(y) \\ \delta_Z(y) \end{pmatrix} \tag{5}$$

$\overline{Z}$ represents the linear error vector in the Z-axis of the milling machine.

$$\overline{Z} = \begin{pmatrix} -z \cdot \varepsilon_{XZ} + \delta_X(z) \\ -z \cdot \varepsilon_{YZ} + \delta_Y(z) \\ z + \delta_Z(z) \end{pmatrix} \tag{6}$$

Where $\varepsilon_X(k)$, $\varepsilon_Y(k)$ and $\varepsilon_Z(k)$ are three rotation errors of an axis k = x, y, z; $\delta_K(k)$ is the position error of axis k = x, y, z; $\delta_K(j)$ with k ≠ j is straightness error in k direction; and ε_{XY} ε_{XZ} ε_{YZ} are squareness errors.

$\overline{T_{LT}}$ represents the translation vector between the coordinate system of the machine CSO and laser tracker CSLT.

$$\overline{T_{LT}} = \begin{pmatrix} oX_{LT} \\ oY_{LT} \\ oZ_{LT} \end{pmatrix} \tag{7}$$

$\overline{R(lt)}$ represents the rotation matrix that links the coordinate system of the machine CSO and laser tracker CSLT.

$$\overline{R(lt)} = \begin{pmatrix} 1 & R_{LTZ} & -R_{LTY} \\ -R_{LTZ} & 1 & R_{LTX} \\ R_{LTY} & -R_{LTX} & 1 \end{pmatrix} \tag{8}$$

Difference between $\overline{X_{LT}}$, provides by the equation of movement, and measured coordinates PLT (xlt, ylt, zlt) shows, among other error sources, the combined influences of MT geometric errors. If this difference is obtained in all workspace of the MT, its volumetric error is obtained.

2.2 Steps to follow in MT volumetric verification process

Tackling verification of any machine tool, the minimum steps to perform are:

1. Generate a CNC program with verification points distribute in the machine tool workspace.
2. Define strategies and measurement conditions.
3. Data processing.
4. Configuration of optimization process
5. Optimization process
6. Representation of results
7. Compensation of geometric errors

The discretization of the MT workspace (step 1) is realised by using a set of points such as: meshes, trajectories or clouds of points in relation with objectives of verification (Figure 3). The behaviour of approximation functions obtained in optimization process (setp 5) depends of verification points used. Therefore, if there is a special area of interest on the workspace of the MT verification points should be focus on this one. Providing the approximation functions obtained a better error compensation in this area [5, 6]. In the same way, measurement conditions and strategies (step 2) are affected by: type of axis of movement of the MT and available space; affecting verification results [6].

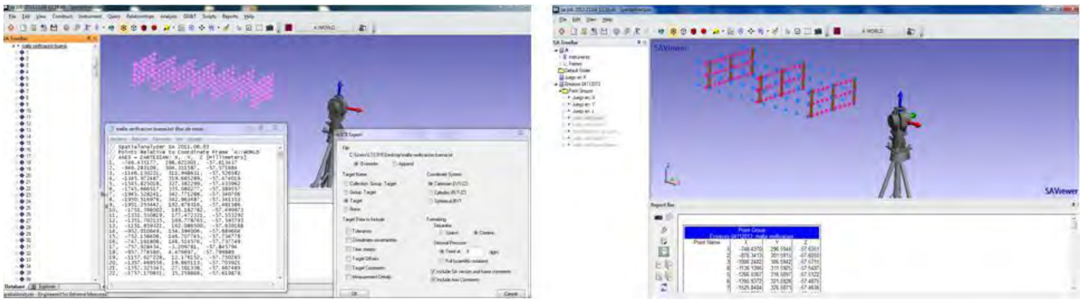

Fig. 3. Discretization of MT workspace – data measurement

Meanwhile steps 1, 2 and 3 are tests characteristic, step 4 affects to optimization process mathematically. As volumetric verification uses non-lineal optimization process based on Levenberg Marquardt algorithm, all parameters introduced on it and their order in optimization affect to verification results. Generally, optimization vector consist on coefficients from approximation functions of geometrical errors to characterize. However, characteristic elements of the MT like offset between axis and the relationship between CS-LT and CSO can be introduced and optimized.

When phases of the optimization and its configuration are defined the optimization process is carried out. The optimization modifies parameters of optimization vectors (coefficients a_i with i=0..n that define approximation functions of errors to characterize, eq. 9).

$$\delta_X(x) \approx \overline{\delta_X(x)} = a_0 + a_1 \cdot x + ... + a_n \cdot x^n \tag{9}$$

The higher degree of approximation functions are defined, the more coefficients must be optimized. Same applies to number of geometric errors to characterize. Optimization modifies optimization coefficients until one on the convergence criteria is satisfied.

At the end of optimization process, regression functions obtained are the approximation functions of each geometric error. These one are used to compensate the combined influences of the MT geometric errors improving its accuracy.

After optimization process and before compensation of geometric errors, the optimization procedure is analysed using a representation module. This one shows information about volumetric error maximum, minimum and average along all process, as well as, the error of each point before and after verification. Similarly, it shows graphically and numerically the approximation functions of each error, histogram of error and colour map before starting and at the end of the optimization (figure 4).

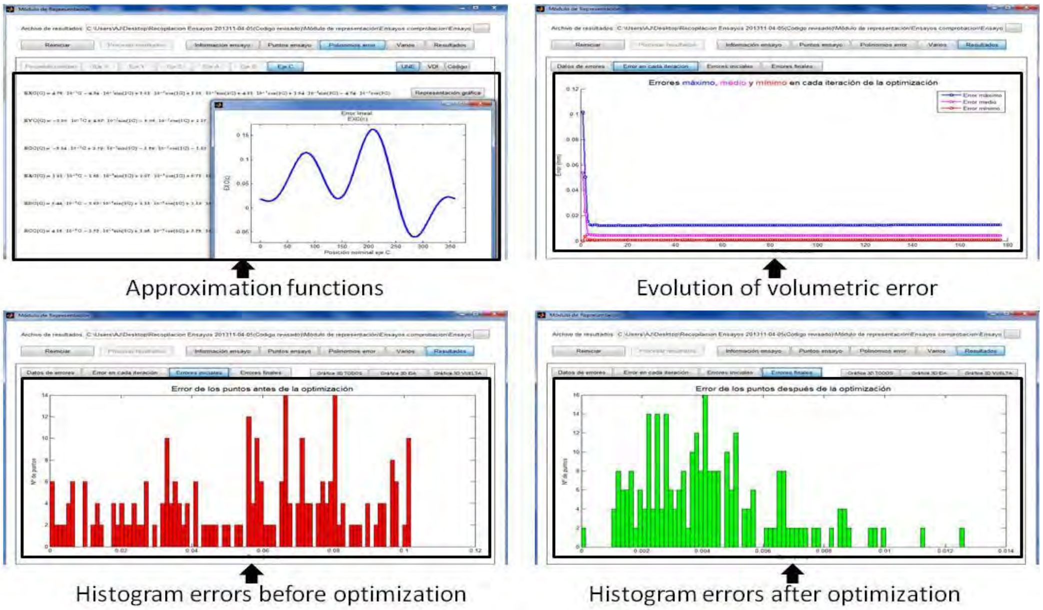

Fig. 4. Representation of results

The most common way to compensate a MT is based on the compensation table of the proper control of the machine. However, current MTs are incorporating new control software that allows compensate each error independently, or generate our own compensation routines using PC. To compensate all machine tools, the kinematic model of the MT can be used as a post-processor of NC program; offering a great flexibility for application of compensation. This method introduces the coordinates of the NC program in the kinematic model of the MT where are affected by approximation function obtained in optimization process. This step creates new coordinates which have associated other errors. Through a process of minimizing based on Levenberg Marquard method, the coordinates that minimize the error in the nominal point are obtained.

To test the behaviour of these functions in none verification points different procedures can be used:

- Testing the behaviour of control points not used in the verification.
- Re-measured of post-processing of original NC program using the approximation functions obtained in verification process.
- Used of an external and more accuracy measurement system from which compare the accuracy of the MT before verification and after compensation process.

3. Results and discussion

With the aim of validate this volumetric verification techniques as a real solution to machine tool verification, an Anayak milling machine with XFYZ configuration and control software Fagor 8025 presented in figure 1 was verified.

Laser tracker positions determine the machine tool workspace in which points used in verification are located. Verification points were defined as a mesh of points distributed in a machine tool workspace with $0 \le X \le 500$, $0 \le Y \le 400$ $0 \le Z \le 200$ (table 1).

Table 1. Machine tool workspace

Axis	X nominal	Y nominal	Z nominal	X to verify	Y to verify	Z to verify
Initial (mm)	0	0	0	0	0	0
Final (mm)	1400	600	300	500	400	200
Interval (mm)				100	100	100
Overshoot (mm)				10	5	5

Firstly, a NC program with points to measure was created in relation with MT discretization of table 1. These points define an uniform distribution of points. As control software might be different to each machine, head, close and stop time at each measure can be changed easily. The second step defines measurement and conditions strategies. Due to MT configuration the laser tracker must be located above X axis, the range of axis of movement to verify is reduced in all axes (table 1). Similarly, the influence of all geometric errors can be measured in a unique position of laser tracker.

Not all measured points are verification points, there are also overshoot points and points of change of direction which must be eliminated from measure and nominal mesh. Furthermore, some nominal points are frequently lost during measurement and must be eliminated too. The next step, configuration of optimization process, was defined with the following conditions:

- Convergence criteria → Number of iterations 50. Maximum functions evaluated 1–20. Minimum variations step 1–10. Maximum variation on objective functions 1–6.
- Regression functions to use →Simple polynomial grade two.
- Optimization method → 1 Phase (squareness + translation + rotation) with one loop optimization.

Optimization process obtains the approximation functions of the MT using only information from verification points. Therefore, verification points should improve their accuracy. To validate adequacy of approximation functions outside verification points a set of control points are affected by approximation function obtained during optimization process. The colour maps of figure 5 show the error distribution of verification points initially (right up) and at the end of the process (right down), similarly, the colour maps situate on left up and left down show the error of control points before optimization an at the end of it respectively.

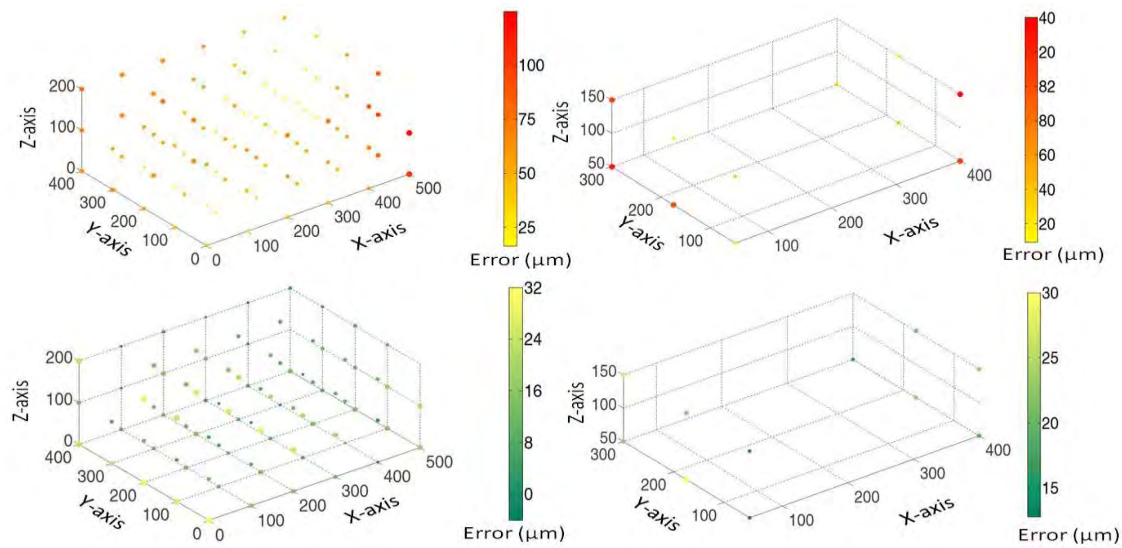

Fig. 5. Colour maps of verification & control points

Table 2 presents the results of verification process. It shows results of verification and control points before verification an after optimization,as well as, accuracy of verification points after compensation process (step 7). As can be observer, volumetric verification improves the accuracy of verification and control points during optimization and after compensation process. However, this one is a bite smaller than optimization as a result of an improvement of LT positioning during optimization. Verification and control points were measured with same LT positioning, meanwhile compensation points were measured after changed the location of LT to avoid a fictitious improvement of MT positioning.

Table 2. Verification results

	Optimization process					
	Initial error (µm)			Final error (µm)		
	Maximum	Average	Minimum	Maximum	Average	Minimum
Verification Points	101,9	63,1	30,5	32,3	14,9	3
Control Points	82,1	66,2	52,5	28,5	20,1	14
	Compensation process					
	Initial error (µm)			Final error (µm)		
	Maximum	Average	Minimum	Maximum	Average	Minimum
Verification Points	101,9	63,1	30,5	38,15	21,8	5,16

4. Conclusions

This paper presents a general method for volumetric verification of a machine tool based on its kinematic model including its measurement system. The LT must be positioned on part place of the machine; the LT must be introduced into the kinematic model of the MT. This will determine the MT workspace to be verified.

Presented results show that volumetric verification is a technique which provides a real improvement on the accuracy of machine tools. The approximation functions obtained improve the positioning accuracy of the MT over an 60 percent both in verification points as in the rest of the machine tool workspace; reducing the verification time to one and a half hour in this MT.

5. Acknowledgements

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